HPC LESSONS FROM 30 YEARS OF PRACTICE IN CFD TOWARDS AIRCRAFT DESIGN AND ANALYSIS

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• Polytechnique Montréal, especially students/researcher
• Internet, a few illustrations
• CHIUW 2021 organizing committee
OUTLINE

• Crash course in Aircraft design (short of being Rocket Scientist)

• Crash course in Aerodynamic Analysis and Design

• Computational Fluid Dynamics (CFD)

• HPC
  • Case studies
  • Chapel breakthrough

• Conclusion

• Vision
What’s special about Montreal?

- 3rd largest aerospace cluster, behind Toulouse (Airbus), Seattle (Boeing)
- Only region where, should you isolate it, an entire aircraft can be designed, built, flight tested and manufactured!
- Hosts the International Civil Aviation Organization (ICAO), United Nations and International Air Transport Association (IATA): international consensus on solutions towards global warming, secure flights and planet-friendly travel (i.e. recycling).

- Notables:
  - Industries: Bombardier, Pratt&Whitney Canada, Bell Helicopter (Civil), CAE (flight simulators), 2\textsuperscript{nd} and 3rd tier: Landing gear, flight controls, etc.
  - Best Student Universities: no. 1 city in North-America (182 000 students), ahead of no. 2 Boston (150 000). Worldwide ranks no. 6. (QS ranking, 2019)
  - World-class AI hub, lead by prof. Yoshua Bengio (Turing award, 2018 with Geoffrey Hinton, and Yann LeCun)
AIRCRAFT DESIGN THEORY -> 4 PHASES (EASY!!!)


0. 1. 2. 3. 4.

Commercial service
AIRCRAFT DESIGN THEORY -> 4 PHASES (EASY!!!)

AIRCRAFT DESIGN REALITY -> SEVERAL PHASES

How to treat aerodynamics?
How to treat aerodynamics?

- Key performance metric (Drag)
- Key security metric (stall, buffet)
- Key aircraft program development metric
  - 1st wind-tunnel tests
  - 1st flight tests
- Historical source of major catastrophes
  - Technical, human, financial
METHODS USED FOR AERODYNAMIC ANALYSIS

Flight tests ~100 000$/hr
Prototype: 1 Billion$

Wind-tunnel tests ~1000-10 000$/hr
Prototype: 10 Millions$

CFD ~100-1000$/hr
Prototype: 1 Million$
AIRCRAFT/AERODYNAMIC DESIGN

Physics
Viscous flows,
Subsonic/Transonic/Supersonic regimes
Multi-physics: icing,
Laminar-turbulent transition

Applied mathematics
Non-Linear Partial Differential Equations
Elliptic/Parabolic/Hyperbolic
Discretization

HPC
Source code, cache, shared-distributed memory
Heterogeneous systems: CPU, GPU, mixed-precision arithmetic
NUMERICAL METHODS: APPLICATIONS

Physics
Transonic buffet

Applied Mathematics
Elliptic, parabolic and hyperbolic flows

HPC
Source code, CPU

Hyperbolic
Mach > 1

Elliptic
Mach < 1

Parabolic
Viscous Boundary-Layer
**CFD WORKFLOW**

Physics

Applied Math.

**Geometry parameterization (NURBS, CAD)**

**Geometry discretization (Surface Mesh)**

Macro \[\rightarrow\] Micro

Volumetric mesh generation

10-1000 Millions unknowns

solution:

i) flow, ii) droplets

Source code

HPC

Time-advancement & post-processing
Numerical analysis allows numerical optimisation

Analysis workflow

Optimisation algorithms

Key for success
• Model precision (physics, numerical, geometry)
• Computing resources and algorithm robustness
• Orthogonal Dimensional Space

Parameterisation

Ichrome.com

Gradient-based (Newton)
~100 evaluations

Brigham Young University

Gradient-free (genetic)
~10^6 evaluations
PHYSICS: TURBULENCE

- All flows can be laminar
- All laminar flows can transition to turbulence
- Turbulent flows contain eddies
- Large eddies transfer energy to smaller eddies...until the smallest eddy dissipates into heat! (Kolmogorov scale)

Source: ase.uc.edu
SEVERAL EQUATIONS AT OUR DISPOSAL... ALL LINKED TO HPC RESOURCES

Navier-Stokes
- DNS
- LES
- DES
- URANS

Turbulence
- RANS

Steady flows

Non-viscous
- Euler
- Irrotational
- Full Potential
- Isentropic
- Transonic Small Disturbance
- Incompressible
- Laplace

High-Reynolds
- Boundary-Layer

Not in industry

Speedup vs RANS
- 10x
- 100x
- 1000x

In industry

Asymptotic coupling
NASA funded a one-year study effort with a world-class team from Boeing, Pratt & Whitney, Stanford University, The Massachusetts Institute of Technology, The University of Wyoming and The National Center for Supercomputing Applications to develop a long-range plan for the development of the next generation simulation-based aerospace design process.

This report, published in March 2014, presents the findings and recommendations of this multidisciplinary team, whose goal was to formulate a knowledge-based forecast and research strategy for developing a visionary computational fluid dynamics (CFD) capability in the notional year 2030.
NASA should:

1. Develop, fund and sustain a base research and technology development program for **simulation-based analysis and design technologies**.

2. Develop and maintain an integrated simulation and software development infrastructure to **enable rapid CFD technology maturation**.

3. **Make available and utilize HPC systems for large-scale CFD development and testing.**

4. Lead efforts to develop and execute integrated experimental testing and **computational validation campaigns**.

5. **Develop, foster, and leverage improved collaborations with key research partners and industrial stakeholders across disciplines within the broader scientific and engineering communities.**
NASA CFD VISION 2030 STUDY: ROADMAP

TRL
LOW
MEDIUM
HIGH

Technology Milestone
Technology Demonstration
Decision Gate

2015
2020
2025
2030

HPC
CFD on Massively Parallel Systems
PETASCALE
Demonstrate implementation of CFD algorithms for extreme parallelism in NASA CFD codes (e.g., FUN3D)

CFD on Revolutionary Systems (Quantum, Bio, etc.)

2025
Demonstrate efficiently scaled CFD simulation capability on an exascale system

30 exaFLOPS, unsteady, maneuvering flight, full engine simulation (with combustion)

2030

Physical Modeling

Improved RST models in CFD codes

Highly accurate RST models for flow separation

Unsteady, complex geometry, separated flow at flight Reynolds number (e.g., high lift)

WMLES/WRLES for complex 3D flows at appropriate Re

Unsteady, 3D geometry, separated flow (e.g., rotating turbomachinery with reactions)

Grid convergence for a complete configuration

Multi-regime turbulence-chemistry interaction model

Production scalable entropy-stable solvers

Algorithms

Convergence/Robustness

Automated robust solvers

Scalable optimal solvers

Large scale stochastic capabilities in CFD

Uncertainty Quantification (UQ)

Characterization of UQ in aerospace

Reliable error estimates in CFD codes

Uncertainty propagation capabilities in CFD

Automated in-situ mesh with adaptive control

Geometry and Grid Generation

Fixed Grid

Tighter CAD coupling

Large scale parallel mesh generation

Creation of real-time multi-fidelity database: 1000 unsteady CFD simulations plus test data with complete UQ of all data sources

Adaptive Grid

Production AMR in CFD codes

On demand analysis/visualization of a 10B point unsteady CFD simulation

On demand analysis/visualization of a 10B point unsteady CFD simulation

Knowledge Extraction

Integrated Databases

Simplified data representation

On demand analysis/visualization of a 10B point unsteady CFD simulation

On demand analysis/visualization of a 10B point unsteady CFD simulation

Visualization

Define standard for coupling to other disciplines

High fidelity coupling techniques/frameworks

Robust CFD for complex MDAs

Integration of UQ for MDAO

MDAO simulation of an entire aircraft (e.g., aero-acoustics)

UQ-Enabled MDAO

MDAO
• The scientific body coordinates several international workshops with aim to improve modeling capabilities on HPC systems
  • Drag, Supersonic, Aeroacoustics, High-Lift, Aeroelastic, Stability and control, Geometry, Hover Prediction, High-order Schemes, etc.

• Notable Participants
  • Industries: Boeing, Lockheed, GE, Textron, Bell, Bombardier (Canada), Embraer (Brazil), Dassault (France)
  • Research Centers: NASA, ONERA (France), NRC (Canada), JAXA (Japan)
  • Universities: Stanford, Oxford (UK), NTNU (Norway), Polytechique Montreal (Canada)
  • Certification agencies: FAA, EASA (Europe), Transport Canada
SOFTWARE AND HARDWARE

• CFD Software provides competitive advantages
  • Many developed by national research centers
    • OVERFLOW, FUN3D, CFL3D, USM3D, etc. (NASA)
    • ELSA, CEDRE (ONERA)
    • TAU, FLOWer (DLR)
  • Many are tagged with export control

• Several are developed by industries, tagged proprietary
  • GGNS (Boeing)
  • FANSC/Dragon (Bombardier)
  • Xflow (Dassault)

• Some developed by universities, open-source or research codes
  (non-commercial licence)
  • SU2 (Stanford)
  • Xflow (Michigan)
  • Diablo (UTIAS)
  • Champs (Polytechnique Montréal)
CFD HISTORY

Parallel programming shift (MPI)

Shared memory

1990
- Convex C220 (2 processors)
- Cray J916 (16 processors)
- Cray SV1 (32 processors)

2006
- IBM - P575 (192 processors)

Today
- > 15,000 processors

Fortran → C → C++ → Chapel
- Various fluid models with a large variation in problem size

Geometry fidelity

High-Lift 3D RANS (~300,000,000 DOF)

High-Speed 3D RANS (~60,000,000 DOF)

Panel Method (~20,000 DOF)

VLM (~500 DOF)

Euler (~100,000 DOF)

2D RANS (~500,000 DOF)
LAB HISTORY AT POLYTECHNIQUE

- **NSCODE** (2012 - early 2020):
  - Shared memory 2D/2.5D structured multi-physics solver written in C/Python
  - ~800 C/header files: ~120k lines of code
  - Run by Python interface using f2py (f90 APIs)
  - Difficult to maintain at the end or even to merge new developments

- **(U)VLM** (2012 - now):
  - ~5-6 versions in different languages (Matlab, Fortran, C++, Python, Chapel)
  - The latest version in Chapel is integrated in CHAMPS

- **EULER2D** (early 2019):
  - Copy in Chapel of a small version of NSCODE as benchmark between C and Chapel that illustrated the Chapel language potential
  - ~10 Chapel files: ~1750 lines of code

- **CHAMPS** (mid 2019 - now):
  - Distributed memory 3D/2D unstructured multi-physics solver written in Chapel
  - ~120 Chapel files: ~48k lines of code
CHAMPS - CHApel Multi-Physics Simulations

- Written in Chapel:
  - Promotes programming efficiency
  - Simpler to learn for new students than C
  - Distributed memory is easier to develop for new students than with MPI
- Initially developed by 3 students until it worked enough to mention its existence
- Relies heavily on object oriented coding with generic types to promote modularity and code reuse
- Compatibility with GPU is being added: See presentation from Anthony Bouchard later today at 2:15pm PDT

- Applications:
  - Aerodynamic simulations in steady/unsteady/frequential domains and for stability analysis
  - Icing: droplet trajectory, thermodynamic models, deterministic and stochastic ice growth
  - Aeroelasticity
  - 2D mesh generation

- World-class CFD code:
  - Participation in the 1st AIAA icing workshop (2021)
  - Participation in the 4th AIAA High-lift workshop (2021)
Icing requires multiple physical models to run in an iterative sequence at the end of which the geometry is deformed
- A lot of potential bugs and failures!
- Almost everything done in the lab becomes connected
- 3D is at the edge of actual world-wide capability in icing

Experimental glaze ice on 3D swept wing

Ref: AIAA Paper 2014-2200

Ref: AIAA Paper 2014-2613
• Droplet seeding point location and freezing depends on Pseudo-Random Numbers along physical models

• Stochastic icing is being developed inside CHAMPS (See presentation from Hélène Papillon Laroche later today at 11:15am PDT)

• Previously developed in NSCODE with more programming challenges in C than in Chapel since growing mesh
  ○ Memory management
  ○ Parallelism
  ○ Additional types such as heap, list, etc.
● Critical field for the design of commercial aircraft

● Requires the coupling of a Computational Structural Dynamic (CSD) model with a CFD model

● Flutter is a dangerous instability that can lead quickly to structural failure
- High-fidelity aeroelastic simulations are complex
- The computational grids for the CSD and CFD model are not coincident
- Efficient algorithms are required to move the structure and the fluid mesh, while keeping the grid’s quality

Ref: A Review of Industrial Aeroelasticity Practices at Dassault Aviation for Military Aircraft and Business Jets. doi: 0.12762/2018.AL14-09
The drag prediction workshop showcases the state of the art for the prediction of the aerodynamic performance of aircraft in cruise conditions, with participation from laboratories (NASA, ONERA, DLR, JAXA, etc.) industries (Boeing, Airbus, Embraer) and universities.

Ref: AIAA Drag Prediction Workshop 5 Summary presentation
The high lift prediction workshop showcases the state of the art for the prediction of the aerodynamic performance of aircraft in take-off and landing configuration, with participation from laboratories (NASA, ONERA, DLR, JAXA, etc.) industries (Boeig, Airbus, Embraer) and universities.

Verification: 2D high-lift 3 elements ai

FUN3D is a CFD code actively developed at NASA.
Final goal: Predict the maximum lift coefficient of civil aircraft

Mesh of 300 million cells (i.e. 1.8 billions unknowns)
Experiments: AoA 17.98 deg

Champs: AoA 17.05 deg
SUMMARY: aircraft/aerodynamic design

• Aerodynamics is key within the aircraft design process
  • 3 phases: conceptual, preliminary, detailed

• Aerodynamic analysis relies on:
  • Physics, applied mathematics, HPC
  • A complex numerical workflow: parametrization, CAD, mesh, solver, post-processing

• Aerodynamic optimisation relies on:
  • Accuracy of the model
  • Computational resources (time, memory)
SUMMARY: modeling takeways

- The model accuracy is related, through the mathematical properties, to computing resources
- Several models are necessary to satisfy each design phase

<table>
<thead>
<tr>
<th>Phase</th>
<th>Accuracy</th>
<th>Computation time</th>
<th>Examined configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td>conceptual</td>
<td>low</td>
<td>short</td>
<td>millions</td>
</tr>
<tr>
<td>preliminary</td>
<td>mid</td>
<td>mid</td>
<td>hundreds</td>
</tr>
<tr>
<td>detailed</td>
<td>high</td>
<td>long</td>
<td>10-20</td>
</tr>
</tbody>
</table>

- The change in accuracy between each phase brings further costly iterative cycles
HPC

• HPC advances have had a tremendous effect on the aerospace industry (aerodynamics, structures, electromagnetics, flight simulation, etc.);

• Hardware: shared to distributed memory, CPU to GPU;

• Software: Strongly typed (FORTRAN) to abstract languages (C++), novel parallel paradigm (Chapel);

• Multidisciplinary knowledge is key for future advances, enacted through new multidisciplinary collaborative efforts (Modelers, Mathematicians, Computer Scientist, etc.);

• These challenges are all captured within NASA’s vision, embraced by the international community.
Questions?

• Special thanks to the organizing committee for this much appreciated invitation, and to HPE/Chapel team/developers for helping our research laboratory and our community.

• Safe, happy and planet-friendly flying!